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ENERGY POTENTIAL OF MODERN LANDFILLS

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ABSTRACT

Methane produced by refuse decomposition in a sanitary landfill can be recovered for commercial use. Landfill methane is currently under-utilized, with commercial recovery at only a small percentage of U.S. landfills. New federal regulations mandating control of landfill gas migration and atmospheric emissions are providing impetus to methane recovery schemes as a means of recovering costs for increased environmental control. The benefits of landfill methane recovery include utilization of an inexpensive renewable energy resource, removal of explosive gas mixtures from the subsurface, and mitigation of observed historic increases in atmospheric methane. Increased commercial interest in landfill methane recovery is dependent on the final form of Clean Air Act amendments pertaining to gaseous emissions from landfills; market shifts in natural gas prices; financial incentives for development of renewable energy resources; and support for applied research and development to develop techniques for increased control of the gas generation process in situ.

INTRODUCTION AND BACKGROUND

The organic components of refuse buried in a sanitary landfill decompose under anaerobic conditions with resulting production of landfill gas. Landfill gas is approximately half methane and half carbon dioxide with minor amounts of other gases. Because of its methane content, the gas has an energy value of about 500 Btu/SCF (19 MJ/SCM). Landfill gas can be recovered for commercial use by means of vertical wells drilled in a completed fill or horizontal collector systems placed concurrently with filling. At the present time, commercial recovery takes place at 242 sites in 20 countries, with a total energy output of approximately 5×10^{13} Btu/yr; about 78% of this total is from more than 100 U.S. sites (Richards and Aitchison, 1990). These sites are a small percentage of the 6,000 or so existing landfills in the U.S. (Brown, Fallah, and Thompson, 1986), suggesting additional potential for commercial recovery.

Utilization options include (1) direct use in gas-fired boilers, the least expensive alternative; (2) on-site generation of electricity; and (3) production of a substitute natural gas through carbon dioxide removal, the most expensive option. Since the economics of any given project are driven by the negotiated price of gas or electricity paid by the user, it is important to finalize user arrangements before installing a recovery system. A young industry, the first commercial landfill gas recovery project was in 1975 at Palos Verdes, California. Today the largest project is a 50 MW steam turbine power plant at the Puente Hills Landfill, Whittier, California.

Two new sets of federal landfilling regulations are also providing impetus to gas recovery projects as a means of recouping required costs for environmental control measures. First, new federal landfilling regulations under Subtitle D of RCRA require gas migration control. Second, soon-to-be-proposed amendments to the Clean Air Act will regulate atmospheric emissions from large landfills.

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This paper will discuss the controls on methane generation in landfills. In addition, it will address how landfill regulations affect landfill design and site management practices which, in turn, influence decomposition rates. Finally, future trends in landfilling, and their relationship to gas production, will be examined.

CONTROLS ON LANDFILL METHANE GENERATION

Refuse decomposition in sanitary landfills occurs through a complex series of microbial decomposition reactions under predominantly anaerobic conditions (absence of air). All of the necessary microbes are present in refuse and soil materials at the landfill site. The terminal reaction is the production of methane by methanogenic bacteria, which are strict anaerobes and function best at near-neutral pH. In effect, the landfill functions like a high-solids, low moisture content anaerobic digester in the ground. Decomposition extends over decades since natural biodegradation rates are low.

Literature pertaining to laboratory decomposition studies of fresh refuse yields a wide range of gas production rates, with extremes from about 7.3×10^{-3} to 3.2 m^3 (total gas) dry Kg-1 yr-1 (Rovers and Farquhar, 1973; Buivid, 1980; Halvadakis, Robertson, and Leckie, 1983). However, lack of standardized sampling methods, incubation techniques, and parallel controls makes comparison between studies difficult. Amendments that have been proposed for increased gas production and used in previous studies include moisture, sewage sludge (a source of microorganisms, nutrients, and moisture), nutrients, and buffers. In a recent study, Barlaz et al. (1989), using a standardized shredded refuse, accomplished decomposition of approximately 70% of the cellulose and hemicellulose in 111 days with modest moisture addition, initial neutralization, and leachate recycle.

Laboratory studies which incubated actual landfill samples under anaerobic conditions indicated rates ranging from 10^{-3} to 10^{-1} m^3 (total gas) dry Kg-1 yr-1 (Jenkins and Pettus, 1985; Emberton, 1986; Bogner, 1990a). The wide range of rates reflects the wide range of refuse composition, nutrients, and moisture which may be present at different locations, even within a single landfill site. The results of Emberton (1986) suggested increased gas production rates from samples with increasing natural moisture content.

Field test cell projects can also yield useful rate information. A large field test cell project in Mountain View, CA, realized rates of approximately $3.2 \times 10^{-2} \text{ m}^3$ dry Kg-1 yr-1 in the control cell (Pacey and Dietz, 1986). A large field test cell project in progress at the Brogborough Landfill, England, showed initially higher rates of gas production from a sewage sludge-amended cell; however, cumulative gas production from each of the six cells with various treatments is now about equal after more than a year of monitoring--further moisture manipulations are planned (Campbell and Croft, 1990).

Practically, landfill gas developers will assume an ultimate gas potential of 6.2×10^{-2} to $1.1 \times 10^{-1} \text{ m}^3$ dry Kg-1 (1.0-1.8 SCF dry lb^{-1}) and apply a first order decomposition reaction to model gas production over a 20-30 year lifetime (Pacey, 1990). It is important to note that the high figure is less than half the gas theoretically obtainable by complete anaerobic biodegradation, emphasizing the inefficiency of landfill anaerobic digestion. Field pumping tests are used to determine maximum sustainable pumping rates which are, in turn, equated to gas generation rates these have suggested maximum rates of $7.5 \times 10^{-3} \text{ m}^3$ dry Kg-1 yr-1 (EMCON, 1981). Typically, the results of decomposition modeling and field pumping tests are compared and merged when making long-term predictions for a particular site.

Controlled laboratory studies suggest the benefit of increased control of the landfill decomposition process. Table 1 indicates gas generation rates from laboratory in-vitro studies of actual landfill samples due to moisture or moisture-plus-nutrient addition. Note that the addition of a comprehensive aqueous nutrient media for anaerobic digestion was of some benefit but did not produce substantially superior results over the addition of water alone. This was due to the fact that the majority of samples contained interbedded calcareous soils with high indigenous nutrients which contributed nutrients, neutralizing capacity, and microorganisms. Thus, it is important to consider the properties of the soils into which filling occurs with respect to the decomposition process. In addition, Table 1 indicates decreases in variability in landfill gas generation rates with addition of water or water-plus-nutrients. Thus, more control of the gas generation process is possible with manipulation of moisture and addition of nutrients. The samples indicated in Table 1 were amended to approximately 200% water content (based on % dry weight), which is at the low end of moisture contents for conventional anaerobic digestion and is termed "high-solids" anaerobic digestion. The literature and recent operating experience suggest that good rates of biogas production can be realized in high-solids digestion (Jewell et al., 1982; Wujcik, 1980; Six and DeBaere, 1990).

Table 1. Summary of cumulative biogas production after 200 days controlled anaerobic incubation at 35°C. Means of triplicate or quadruplicate biochemical methane potential assays of landfill samples from three sites. Water and aqueous nutrient media added to equalize water content at approximately 200% (based on % dry weight) for comparison with unamended controls. See Bogner, 1990a, for detailed discussion of methods and results.

	Mean total gas (mL)	Mean rate (m^3 dry Kg-1 yr-1)	$\frac{\text{Rate}}{\text{Rate control}}$	N
Controls	273	3.31×10^{-2}		16
Water added	677	7.16×10^{-2}	2.16	16
Aqueous nutrient media added	852	9.16×10^{-2}	2.77	12

Ranges for rates (m^3 dry Kg-1 yr-1): controls 1.3×10^{-3} to 1.7×10^{-1}
water 1.2×10^{-2} to 2.0×10^{-1}
nutrient 3.5×10^{-2} to 1.8×10^{-1}

At any given location in a landfill site, the degree of decomposition may be negligible to highly advanced. Visual evidence indicates that both readable newspapers and green grass may coexist in a single site with dark gray sludges indicative of an advanced state of decomposition (low residual volatile solids). Thus, the observed gas production from a given well is a function of gas pumped from a cumulative volume of landfill containing variable gas production rates. It seems clear that the degree of variability within a given site may be at least as great as the variability between sites. For example, in the study cited in Table 1, the highest and lowest gas production rates among the controls were from samples taken at approximately the same depth at the same site; the rates varied by more than two orders of magnitude. Since complex relationships exist between the various groups of microorganisms and their substrates to accomplish landfill degradation of complex organic materials, greater process control is attainable only with increased homogeneity within the landfill. Some engineering measures to accomplish this will be discussed in greater detail later in this paper. Ideally, though, greater moisture contents combined with particle size reduction are key to bringing degradable substrates, bacteria, and nutrients together for more uniform decomposition rates.

ENGINEERING DESIGN, SITE MANAGEMENT PRACTICES, AND CLIMATIC FACTORS THAT INFLUENCE GAS GENERATION AND RECOVERY

Historically, landfills have not been designed for optimization of gas generation and recovery. Rather, they have been designed in accordance with the appropriate state regulations in force at the time the landfill was permitted. These regulations have evolved from more lenient regulations with regard to liquid and gas control in the 1960's-1970's to more stringent regulations in the 1980's and into the 1990's. Specifically, we now have the first federal landfilling regulations under Subtitle D of RCRA. States are free to set more stringent regulations; indeed, California regulations already exceed Subtitle D requirements. In addition, the U.S. EPA plans to regulate gaseous emissions from landfills into the atmosphere (both methane and volatile organic compounds); these regulations will be formalized in proposed amendments to the Clean Air Act that will pertain to active, large landfills.

It is paradoxical to compare the design goals of older and newer landfill sites with respect to refuse decomposition and landfill gas generation. Older landfills, designed in the 1960's and early 1970's under less stringent cover and liner requirements, provided a more open system for infiltration of rainfall, surface water, and groundwater, thus encouraging increased decomposition rates. However, they often did not provide good containment for and control of the gaseous and liquid products of decomposition. Newer sites, on the other hand, are designed to provide a high degree of containment with low decomposition rates. Key features of modern landfills include covers that promote high rates of runoff with minimal infiltration, prohibition of liquid wastes, multiple barrier liners, and leachate collection and disposal systems. Landfill leachate typically contains high concentrations of intermediate decomposition products which are substrates for methanogenic bacteria; by removing leachate and sending it to sewage treatment or alternative disposal, substantial methane potential is lost from the landfill "digester."

It is useful also to examine general climatic factors with regard to landfill decomposition, particularly precipitation and temperature. Most landfills, regardless of climatic region or season, are mesophilic -- with internal temperatures in the 30-35°C range. In a very few cases, landfill temperatures of 50-55°C indicative of thermophilic conditions with accelerated decomposition rates have been recorded. Precipitation is less of an influence at newer sites designed for a high degree of containment than it was at older, more open sites. Refuse contains entrained moisture and yields additional water during decomposition reactions. Thus, one can readily observe gas production at semiarid containment sites. However, at some such sites, yields to a commercial recovery system may be less than anticipated, with resulting mismatch of recovery hardware to gas production rates.

ENERGY POTENTIAL FROM CURRENT AND FUTURE LANDFILLS -- THREE SCENARIOS

In order to discuss the energy potential of modern landfills, one must distinguish between existing sites and some projections for landfilling practices at future sites. Three scenarios were developed to address the methane production potential of current and future landfills.

Scenario I. Existing Sites -- Active and Completed

These operating and closed sites were constructed under a variety of state permit regulations and enforcement levels over three decades. (Note: Prior to the advent of controlled landfilling practices in the 1960's, most communities practiced open dumping and burning with negligible production of methane.) The refuse contained therein is in various states of decomposition. The majority of sites do not have leachate and gas control measures. Nevertheless, where a potential gas user is available, particularly at larger sites, commercial gas recovery may be feasible. An individual site investigation is mandatory, including pumping tests, physical examination of refuse decomposition when test wells are drilled, laboratory testing of soils and refuse, and gas production modeling.

The only type of moisture manipulation permitted under Subtitle D is leachate recycle, provided the site is lined and provided with a leachate collection system. Not only does leachate recycle prevent loss of intermediate volatile fatty acids with methane potential, as discussed above, it also provides additional liquid circulation for contact between microorganisms, nutrients, and degradable substrates. Thus, where feasible, leachate recycle should promote increased gas generation rates. Unfortunately, it is not possible to accurately predict the magnitude of this increase for any given site. In the future, it may be possible to develop combined laboratory and field procedures that will provide meaningful rate information. At the present time, however, the increased benefit vs. the increased cost of a leachate recycle system for a given gas recovery scheme cannot be accurately determined, only weighed against the cost of alternative leachate disposal measures.

Scenario II. New Sites -- Geofills

Prohibitions against yard waste being placed in landfills and aggressive recycling practices for other biodegradables (particularly paper) remove a considerable portion of the methane potential from landfilled refuse. Table 2 indicates the methane potential of various organic fractions of a typical refuse. More than 90% of the methane potential is from cellulose and hemicellulose, major components of plant materials and paper products. Lignin is recalcitrant to anaerobic digestion. Table 3 presents a quick follow-on calculation for the overall decline in total methane potential resulting from removal of paper and plant materials from landfill disposal. Thus, with high recycle rates, the methane potential is drastically reduced.

The resulting landfills with low content of biodegradables plus various types of monofills (such as ash disposal sites) are poor candidates for gas recovery. They can be termed "geofills," since their purpose is to place the waste into geologic storage. Such sites will require stringent hydrogeologic controls and, if there is any potential for gas generation, control measures for gas migration. Such a site is portrayed in Fig. 1. There is no commercial gas recovery potential at such sites and thus no potential for monetary return on cost of filling, other than user fees.

Scenario III. New Sites -- Biofills

"Biofill" is a term coined by the U.K. Department of Energy (Richards and Aitchison, 1990) to describe a landfill that is designed and operated for optimum methane generation and

Table 2. Methane Potential from 1 Kg refuse, Madison, Wisconsin. Data from Barlaz, Ham, and Schaefer, 1989.

	% Dry Weight	Methane Potential L/dry Kg @ NTP Via Anaerobic Digestion
% Volatile Solids, Including:	78.6	
Cellulose	51.2	191.0
Hemi Cellulose	11.9	44.4
Protein	4.2	21.7
Lignin	15.2	---
Soluble Sugars	0.35	1.3
		258.4, with > 90% from Cellulose & Hemicellulose

Table 3. Effect of Cellulose and Hemicellulose Removal on Refuse Methane Potential. Basis: Madison, Wisconsin refuse. See Table 2.

% Cellulose & Hemicellulose lost to Landfill Disposal	Decrease in Methane Potential (L/dry Kg @ NTP)	% Decline in Total Methane Potential - Unit Mass Refuse
10	23.5	9
20	47.1	18
25	58.9	23
50	117.7	46

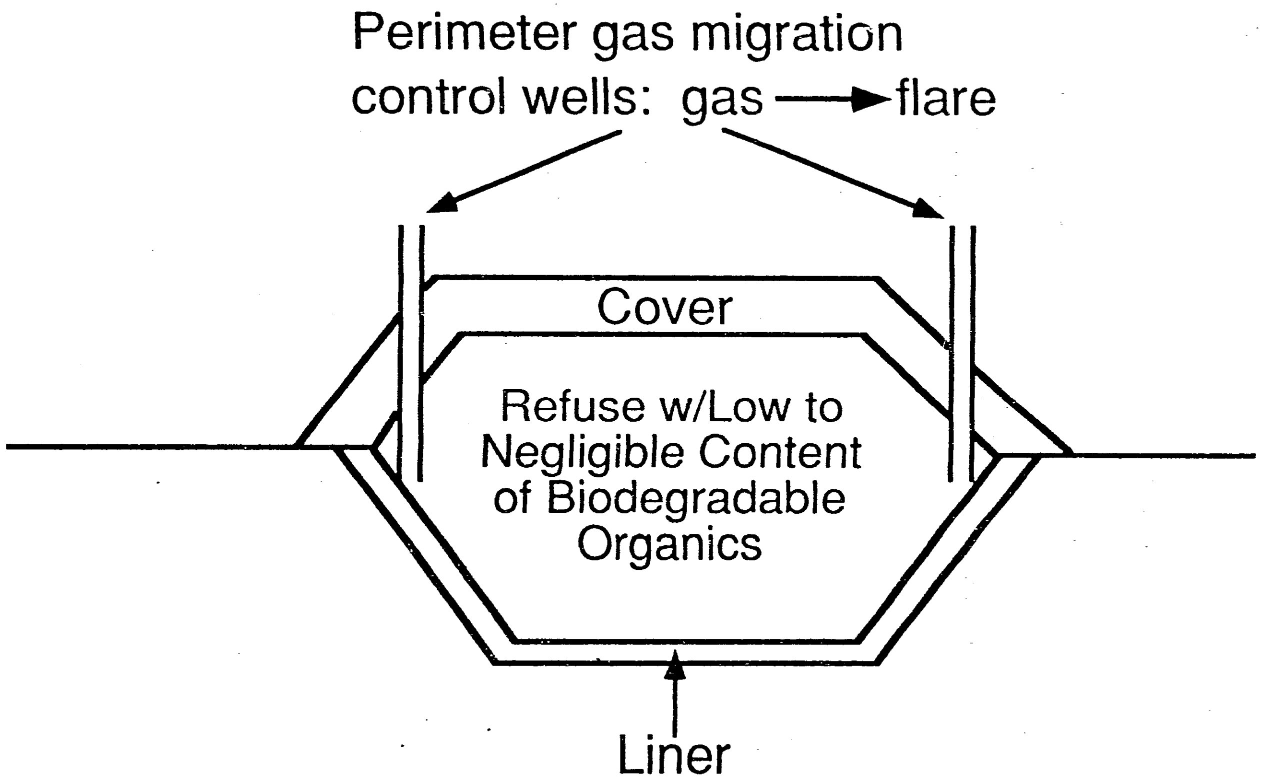
Perimeter gas migration
control wells: gas → flare
Cover
Refuse w/Low to Negligible Content of Biodegradable Organics
Liner

Fig. 1. The Geofill Concept. Commercial Methane Production Potential Negligible. Gas Migration Control Required Where Methane Production Potential Exists. Not Shown are Leachate and Gas Monitoring Wells/Probes.

recovery. This is a landfill that may achieve methane production approaching the values shown on Table 2 through manipulation of refuse placement in a tightly engineered subsurface system with supplemental moisture and other additives (nutrients, buffer, microorganisms). Currently the subject of basic and applied research in the U.K., including the field test cell project mentioned earlier (Campbell and Croft, 1990), the Biofill concept is being developed to extend high solids anaerobic digestion technology to the landfill environment.

For the U.S., Fig. 2 suggests a conceptual design for a modified Biofill that would conform to Subtitle D regulations, which do not permit water or liquid waste to be added to landfills. Included are containment measures (multiple barrier liner and cover systems), leachate recycle, and internal permeable corridors for better moisture distribution through the decomposing refuse. Most new landfills will be designed with strictly engineered liners and covers; thus, the only major additions would be leachate recycle and altered internal design. Some size reduction of refuse and removal of selected nonbiodegradables would also be beneficial. Active gas collection must be concurrent with filling. Groundwater and gas monitoring systems must be extensive to assure containment. Preliminary laboratory testing of refuse and soils is recommended to assist with site design and optimum placement of materials for gas generation and recovery.

The benefits of biofilling include optimum methane generation and recovery, as well as faster stabilization of degradable organics. The latter is especially important at sites pressured by surrounding urban and suburban development to promote land uses more desirable than a long-term refuse repository. With current fills, anaerobic decomposition may extend over a half century or more, as evidenced by nondecomposed organics in fills 20-30 years old. It is perhaps worth repeating that lignin, which is recalcitrant to anaerobic digestion, will remain in landfill storage into geologic time. The geologic record suggests that future conversion of lignin to fossil fuel precursors is possible over very long time frames (Bogner, 1990b).

CONCLUSIONS

The production of methane from anaerobic decomposition of refuse in landfills is a complex process that has been largely uncontrolled in existing landfills. Nevertheless, commercial methane recovery has been achieved at a small percentage of U.S. landfills (over 100 sites). This alternative energy source is a relatively small but immediately attainable source of useful methane. As more stringent engineering measures are implemented under new federal regulations to achieve containment of decomposing refuse and control of its liquid and gaseous products, it is desirable also to promote increased control of the decomposition process within the tightly-engineered landfill system. Some applied research and development will be needed to achieve that control within currently-permitted landfill practices.

In addition to energy benefits, the utilization of landfill methane provides important environmental and safety benefits, including:

(1) capture of subsurface methane, which may form explosive methane/air mixtures in soil gas, at the ground surface, and in overlying structures.

(2) minimization of methane emissions to the atmosphere. Landfills are an important contributor to observed historic increases in atmospheric methane (Bingemer and Crutzen, 1987; Bogner, 1990b), a greenhouse gas implicated in global warming projections.

7.2

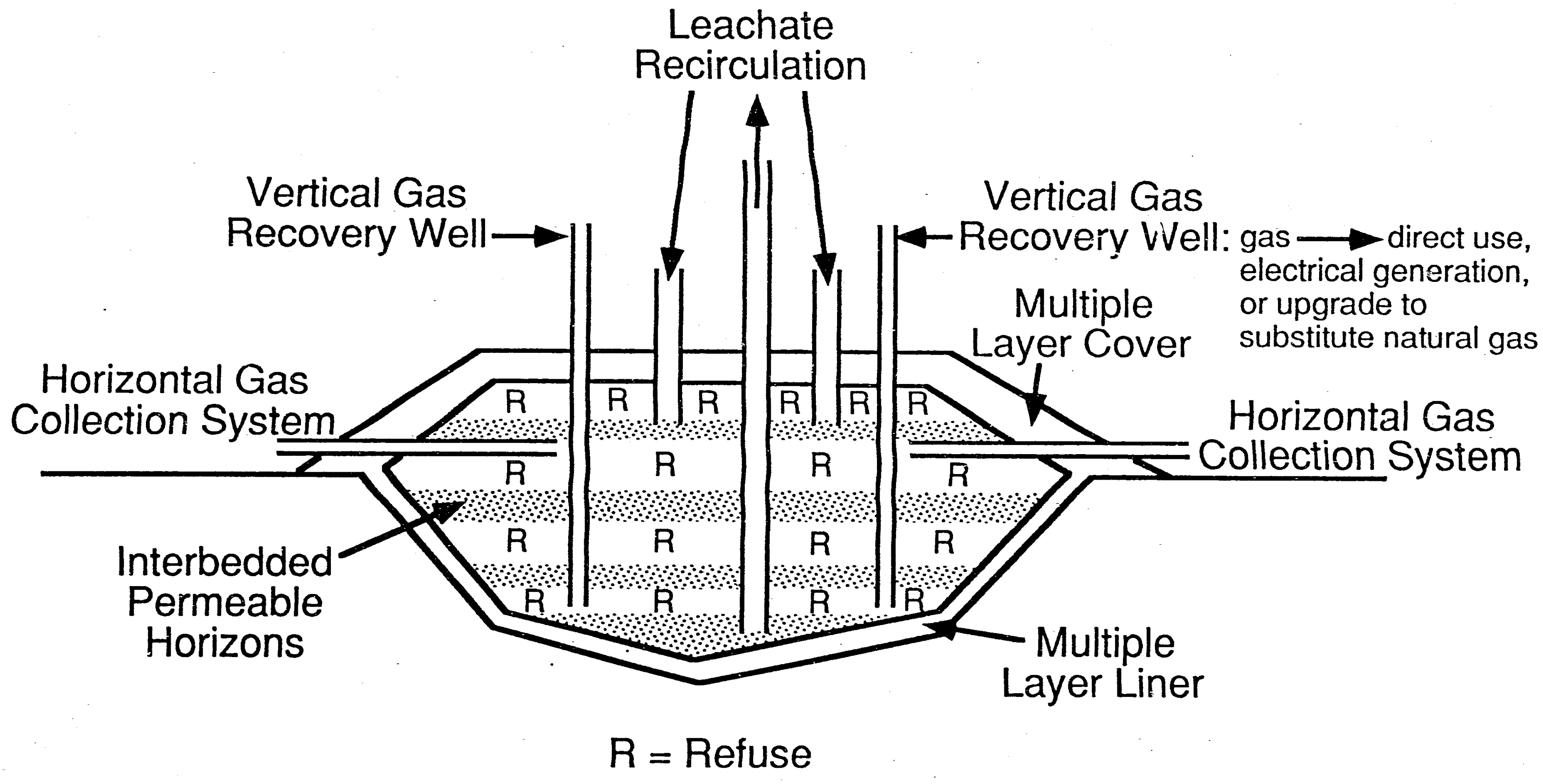
Leachate
Recirculation
Vertical Gas
Recovery Well
Vertical Gas
Recovery Well: gas → direct use,
electrical generation,
or upgrade to
substitute natural gas
Multiple
Layer Cover
Horizontal Gas
Collection System
Horizontal Gas
Collection System
Interbedded
Permeable
Horizons
Multiple
Layer Liner
R
R = Refuse

Fig. 2. Conceptual Design for a Biofill That Could Be Permitted under Subtitle D Regulations. Optimum Methane Production and Recovery with Faster Landfill Stabilization. Not Shown are Leachate and Gas Monitoring Wells/Probes.

To a large extent, current regulations requiring increased landfill gas control are promoting a renewed interest in landfill gas recovery as a potential source of revenue to mitigate increased costs for environmental control. Shifts in natural gas prices and financial incentives for development of renewable energy resources can also stimulate increased commercial development of landfill methane.

In many parts of the U.S., landfilling will continue to be relied upon into the next century as the least expensive waste disposal alternative. To a large extent, refuse collection and landfill disposal are managed cooperatively between public- and private-sector interests. Thus, better control of the decomposition process, which is desirable for both commercial and environmental aims, should be the subject of applied research and development supported by cooperative public/private ventures.

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